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Converters, Compatibility, and the Control of Interfaces

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Abstract. Converters, emulators, or adapters can often make one technology partially compatible with another. We analyze the equilibrium market adoption of otherwise incompatible technologies, when such converters are available, and the incentives to provide them. While market outcomes without converters are often inefficient, we find that, in plausible cases, the availability of converters can actually make matters worse. We also find that when one of the technologies is supplied only by a single firm, that firm may have an incentive to make conversion costly. This may lend some theoretical support to allegations of anticompetitive disruption of interface standards.

Keywords. emulators, adapters, translation, conversion, gateway technology, interfaces, compatibility, standards.

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Joseph Farrell and Garth Saloner

1. Introduction

Compatibility is an essential aspect of conduct and performance in many industries, most notably the information industries. Telecommunications would be unworkable without compatibility, and as commercially-written software, networking, and portability become ever more important compared to stand-alone operation, the computer industry is approaching the same degree of dependence on compatibility.[1]

Compatibility may be achieved through *standardization*: an explicit or implicit agreement to do certain key things in a uniform way. Standardization occurs when computer manufacturers use the same interfaces for attaching peripherals, when cameras are designed to use a common 35mm film format, or when software designers adopt a common user interface. Standardization in turn may emerge through the independent actions of market participants, through the formal coordination activities of voluntary industry standards committees, or through government action.

But standardization has its costs. First, it may retard innovation.[2] Second, the process of standardization may itself be costly. In the case of coordinated standard-setting, these costs include the resources spent on standards committees[3] and the delay costs caused by their slow decision-making processes.[4] In the case of informal market standardization, resources may be spent on

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[1] Several of the papers in the references discuss the benefits of compatibility.

[2] A classic example is the QWERTY typewriter keyboard; see David (1985). For theoretical discussion of such "excess inertia," see Farrell and Saloner (1985, 1986a) and Katz and Shapiro (1986). As those papers show, the opposite bias is also possible.

[3] These direct costs are substantial: for example, a recent National Research Council Discussion Paper (September 22, 1989, for the Crossroads of Information Technology Standards workshop) contained an estimate (page 12) that "the current OSI standards effort has cost the industry approximately $4 billion in time and travel of the participants." Similarly, Elisabeth Horwitt (*Computerworld*, April 20, 1987, page 43) wrote: "Unfortunately, participation in a standards group means sending a technically savvy manager — whose time is expensive — to periodic meetings that are often held on the other side of the country." See also "Users Cry for Standards but Don't Get Involved," *Computerworld*, May 4, 1988 for suggestions that as a result of these costs, users and small vendors are often in practice excluded from the process.

[4] Discussing the process of ANSI standards formation, J.A.N. Lee, then vice chairman of ANSI's X.3

reverse-engineering in order to conform to a recognized but proprietary standard,[5] or else rival technologies may compete to become the *de facto* industry standard.[6] Then, users may suffer transient incompatibility until one technology triumphs, stranding users who have invested in the losing technology; or else neither technology may emerge as a standard, in which case users are doomed to incompatibility. Third — the problem addressed in this paper — since standardization typically constrains product design, it may sacrifice product variety. Since compatibility benefits (network externalities) create an economy of scale on the demand side, this problem is much like the familiar trade-off between variety and production economies of scale.

These problems make standards a significant public-policy issue, and compatibility is often weighed against other goals. For example, the Federal Communications Commission (FCC) decided[7] after much debate, to insist that any transmission standard for high-definition television (HDTV) should, at least initially, be compatible with the current NTSC standard receivers; this, especially in conjunction with the FCC's requirement that single-channel systems may not exceed the current six megahertz bandwidth, substantially constrains the possible adoption of broadcast HDTV systems.

But compatibility can be achieved by other means than standardization, and one might hope that we could thus achieve compatibility benefits without the costs, such as loss of variety, imposed by standardization. The information content of a program or a data file, or of a stream of information coding a conversation, is the same however it is expressed and whatever hardware carries it. In principle, translating from one to another is a routine information-processing task, and the cost of such tasks is falling rapidly. If "black boxes" can readily translate from WordStar

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Committee, remarked, "Our procedures do take time. The average time to produce a standard is about seven years." (Quoted in "Microcomputer Standards: Weighing the Pros and Cons," *IEEE Spectrum*, May 1981, p.50.) See Farrell and Saloner (1988) for a theoretical treatment of these delays, and of the benefits of formal standards-setting.

[5] For example, Phoenix and others partially reverse-engineered the BIOS for the IBM PC; and much effort was devoted to cloning Adobe's proprietary de facto standard PostScript before Adobe reluctantly opened the standard in September 1989 — see for instance Tony Bove and Cheryl Rhodes, "The Race to Imitate PostScript," *Bay Area Computer Currents*, November 3–16, 1987, p26–27.

[6] Saloner (1989) analyzes the current battle between the Open Software Foundation and Unix International to develop standards for computer "open systems". Another current example is IBM's Microchannel Architecture and the rival EISA: see for instance "High-Tech War: Nine Firms that Make Personal Computers Gang Up Against IBM," *Wall Street Journal*, Sept 14, 1988, pp.1,28, or "Pulling the Plug: The Great Boom in PCs May Be Coming to an End," *Barron's*, July 24, 1989, pp8–9, 28–29.

[7] "FCC Announcing Fundamental Policies and Defines Boundaries for Development of Advanced Television," (FCC press release), September 11, 1988.

to WordPerfect, or from Intel to Motorola architectures, it may be unnecessary to standardize.[8] Such converters (also known as translators, emulators, adapters, or gateway technologies) may provide compatibility without constraining variety or innovation. According to this view, progress in emulation technology will, fortunately, soon make standardization unnecessary:[9] using converters, *compatibility* can be achieved *ex post*, *i.e.*, after a variety of products has been introduced, without the constraints of *ex ante standardization*. As David and Bunn (1988) put it: "[N]etwork technologies are not static, and initial technical incompatibilities between variant formulations of such technologies ... can have their economic importance mitigated as a result of the *ex post* introduction of gateway innovations".

Although a given information-processing task such as translating a file is becoming much cheaper over time, this does not imply that compatibility through converters will become almost costless. In fact, the tasks required become more complex and such translation remains costly.[10] Perhaps more importantly, it often degrades performance,[11] especially in network applications, where real-time conversion is required: while it does not matter much if it takes a half-minute to convert your WordPerfect file to WordStar, it may matter a lot (especially in manufacturing applications) if each of your commands to the local network is delayed even slightly. Moreover, conversion technology

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[8] Examples of translation devices are Word for Word, which converts files and documents from one PC-compatible word processor to another, and products offered by Flagstaff Engineering that "connect incompatible computer systems using diskette, tape, communications, or printed media". (Drawn from Besen and Saloner (1989) footnote 62.) And products exist which enable users to transfer files between the IBM PC and the Apple Macintosh: see for instance "Bridging the gap between Macs and PCs," *Computerworld*, May 1, 1989, pages 109–115.

[9] "The long-term consequence of emulation is that it may make computers much more generic, where anybody's computer could run anybody's software. If you have enough horsepower that becomes practical." — Mr Michael Slater, quoted in John Markoff, "Making Computers Compatible," *New York Times*, May 11, 1988, p.C5.

[10] *Datamation*, October 15, 1985, p.88, quotes an estimate from the 1976 *Encyclopedia of Computer Science* that "one quarter of the total available computer power in the US [was] being used to provide conversion systems between dissimilar, nonstandardized (or nonstandard) elements of computer systems," and remarks that "the situation is not much different today."

[11] For instance, the Atari ST equipped with PC-Ditto emulation software (Avant-Garde Systems), which translates Intel 808x instructions into Motorola 68000 instructions, takes almost twenty times as long as the IBM AT to do one standard benchmark task. The Motorola chip is not intrinsically slower; but each instruction to an Intel chip may have to be translated into a number of instructions to the Motorola chip; the latter could have done the task more easily if it had been organized slightly differently. See Philip Nelson, "IBM PC emulator for Atari ST," *Compute!*, November 1987. A similar "incremental compilation" technique is used by Phoenix, Insignia and others to translate MS-DOS instructions so that software can be used by Apple and Sun machines. The reverse translation, while technically feasible, is unavailable because of legal restraints imposed by Apple (Markoff, *New York Times*, May 11, 1988). See also "Bridging the gap between Macs and PCs," *Computerworld*, May 1, 1989, pages 109–115. In data transmission, "protocol converters are effective for low-speed (less than 9.6-kbit/s) data transfer and simple interactive traffic but offer limited speed and throughput for heavy traffic between computers." — *Data Communications*, March 1987, p.191.

typically is available only with some delay.[12]

Thus conversion is not an *ideal* solution to the conflict between compatibility and variety. Our first topic in this paper is the relationship between equilibrium and optimal use of conversion technology. When is it the best solution to the compatibility/variety conflict? Will it emerge as an equilibrium when it should?

Perhaps the simplest summary of our findings is that, while converters reduce the *social* cost of a failure to standardize, they also make such a failure more likely by reducing the *private* cost. This has far-reaching implications for the efficiency of converters.

The details of the outcome and its inefficiencies naturally differ according to market structure. Under "perfect competition," all goods are available at production cost, and the adoption externalities lead to inefficiencies in a relatively straightforward way. As one might expect, a monopolist can internalize some of these externalities and coordination problems; however, other inefficiencies arise in that case. Finally, a duopolistic market has its own pathologies, which we explore.

This discussion assumes that converters are exogenously available, and this leads to our second main concern. It is often alleged that a dominant firm has an incentive to manipulate the interface between its product and those of its rivals, making compatibility more costly to achieve. Such allegations have often been directed at IBM, for example.[13] We show that, indeed, a "dominant" firm may wish to hinder cheap conversion technology.

Summary of Our Model

We examine these questions in a model in which there are two technologies and buyers have heterogeneous preferences. In particular, we suppose that buyers are "located" on a unit interval and that the technologies are located at the extreme points. While each buyer has a locational preference for one of the technologies over the other, his utility is also increasing in the number of other users with whom his product is compatible. Our model therefore captures the trade-off between compatibility and variety.

[12] For instance, IBM only recently made available support for the de facto network standard TCP/IP in its AS/400 series. (*Computerworld*, September 18, 1989, p.51,56). Similarly, "The technology [of protocol conversion in data transfer] has not advanced to the point where one may purchase off-the-shelf products that connect arbitrary equipment and systems," — Internal TRW study, quoted in *Datamation*, August 15, 1986, p.46.

[13] See Adams and Brock (1982) for an exposition of some such allegations and Fisher, McGowan and Greenwood (1983) for an economic analysis from the IBM perspective.

When both technologies are adopted, buyers on one technology are automatically compatible with others on that technology. In addition, users can buy an imperfect converter that gives them *some* of the compatibility benefits from the users on the other technology.

A "one-way" converter enables its owner to derive some network benefits (through conversion) from users of the other product, but does not enable them to derive any corresponding benefit from him. Evidently, *given* his choice of product, no externality is involved in his choice of whether or not to buy such a one-way converter; on the other hand, the availability of a converter may tempt him to buy a minority technology when he otherwise would have bought the more popular product, and this would have network-externality effects. From a business viewpoint, it is always desirable to offer a one-way converter with your product: it enhances your product's value without also enhancing your rivals'.[14]

A "two-way" converter, on the other hand, confers partial compatibility in *both* directions. Once otherwise incompatible technologies have been adopted, there is an externality in a user's decision to buy such a converter: it confers a network benefit on users of the rival technology. This observation suggests that, at least in the duopoly case, a firm's attitude to two-way converters may be ambivalent; we will return to this point below.

Our model has three main parameters of interest: the importance of compatibility benefits, the degree of imperfection of conversion, and the cost of conversion. We characterize the parameter values for which standardization, conversion, and incompatibility equilibria exist, for the case where each technology is competitively supplied (perfect competition), where each technology is provided by a different firm (duopoly), and where both technologies are provided by the same firm (monopoly). We find inefficiencies of different kinds in the three market structures.

Under perfect competition, in our model, when a conversion equilibrium exists, "too many" converters are bought in equilibrium — contrary to the intuition that buying (two-way) converters is a public-spirited action and free-riding will mean that it is done too little. The reason is that, because converters are imperfect, a user who buys the dominant technology may (and in our model does) confer a greater total (positive) network externality on others than does one who buys the minority technology and a converter. Of course, a single user does not properly take account of this, whence our result. As indicated above, the reduction in the private costs of failure to standardize

[14] For example, razor-blade producers used to sell razors very cheaply, intending to take their profits on blades, and would try to design their razors and blades in such a way that their blades would be compatible with other firms' razors, but not vice versa. This led to the weirdly-shaped holes in the middle of razor blades. See Adams (1978), pages 146–150.

may matter more than the reduction in the social costs, and so converters may be harmful. In particular, we find that the existence of converters can actually lead to less compatibility than would occur in their absence — and that this happens precisely when compatibility is most important!

This inefficiency is an example of the *irresponsibility of competition.* It might be better if some good were not offered at all, or were offered only at a high price, because consumers use it "irresponsibly;" but with competition, no agent can decide that a good will not be offered, or that its price shall be high.[15]

One might conjecture that this inefficiency is eliminated, at least in part, when a monopolist provides both technologies. The monopolist can reduce the temptation to desert the mainstream and buy a converter, by pricing the converter and the minority product appropriately. It can then appropriate some of the social gains in its pricing of the basic products. But we show that, on the contrary, the monopolist is even *more* likely to produce inefficient conversion outcomes. The reason is that a monopolist (that cannot price discriminate) can extract only the willingness to pay of the marginal buyer. In a standardization equilibrium, however, the marginal buyer is "located" far from the chosen standard technology, and is therefore willing to pay relatively little for it. The monopolist then often prefers to price in such a way as to induce a conversion equilibrium, in which the marginal buyer on each technology gets large network-independent benefits from that technology. The inframarginal buyers lose compatibility benefits but, since the monopolist cannot appropriate those benefits, it ignores that loss. In short, the benefits of variety may accrue disproportionately to the marginal buyer, and the taste for variety may therefore be too well served by the monopolist when it conflicts with the taste for compatibility, which affects the inframarginal buyers more.

Not only does the monopolist induce users to buy converters for more parameter values than they would under perfect competition, but when it does so, it prices in such a way that more users buy converters than do so in a competitive conversion equilibrium. From a social welfare point of view, too many users buy the converter under perfect competition, and this inefficiency is exacerbated under monopoly.

Under duopoly, this inefficiency may be — and in our example is — even more pronounced. Standardization is less likely under duopoly than under either competition or monopoly. For the "dominant" firm A's above-cost pricing sets up a price umbrella under which firm B can attract defectors

[15] A similar effect can arise in monopolistic competition: see Salop (1979).

from A's dominant technology, even if there would be no such defectors if both goods were priced at cost (as under competition).

The duopoly case also lets us examine the logic of alleged anticompetitive manipulation of interface standards by a dominant firm — in particular, the idea that such a firm might try to make conversion inefficient or costly. We study the incentives for such behavior by examining the comparative statics on the cost and quality of converters. We find that (in our special model) a dominant firm indeed wants converters to be expensive, although (like its rival, and unlike consumers) it prefers efficient to inefficient converters.

Although our model is static, this result suggests that a dominant firm might, for example, refuse to provide crucial interface information that facilitates the construction of a converter, or (in a dynamic framework) it might frequently change an interface without advance notice to the suppliers of the converter. Such behavior on the part of IBM was alleged in the European Economic Community's investigation during the early 1980s, based on complaints by Amdahl and Memorex, who alleged that IBM's practice of withholding details of new interfaces was an abuse of a dominant position.[16]

Related Work

Converters have received relatively little attention in the compatibility and standardization literature.[17] The work most relevant to this paper is that of Katz and Shapiro (1985). They develop a homogeneous-good oligopoly model in which consumers value compatibility. In the duopoly case they examine the incentives of one of the firms to construct an "adapter" (by expending a fixed cost) that makes its product perfectly compatible with the other's.

The trade-off between variety and standardization, which is at the heart of our analysis, does not arise in theirs. Nonetheless some of the same intuitions that underlie their results, underlie some of ours as well. For example, the relative valuations of compatibility for marginal versus inframarginal consumers plays a role in both. In some cases, however, major modelling differences between their model and ours lead to quite different results. In particular, because they assume homogeneous products and elastic demand, they find that an increase in compatibility leads to a decrease in price in equilibrium, whereas (in our duopoly analysis) we find the opposite.

[16] The investigation was ended in August 1984, with a "voluntary undertaking" by IBM to provide timely interface information to competitors. See for instance *Electronic News*, August 6, 1984, pages 1, 4, or *Data Communications*, September 1984, page 52.

[17] Brief discussions are found in Braunstein and White (1985) and Besen and Saloner (1989).

Matutes and Regibeau (1988) analyze a model in which consumers value "systems" composed of components that may be purchased separately (such as stereo components). Consumers care about compatibility only because they like to be able to "mix-and-match" components, and not because of any "network externality". Matutes and Regibeau also examine the firms' incentives to produce compatible components by constructing "adapters" or making design changes. They find that firms have strong incentives to attain compatibility, because (as in our model) compatibility leads to higher prices.[18] Economides (1989) derives the same results in a model with more general consumer preferences, and extends the analysis from duopoly to oligopoly. Economides (1988) extends the Matutes-Regibeau analysis by allowing firms to choose the price at which consumers can attain compatibility. That is, each duopolist, by altering the design of its component, can make it more or less costly for a third party to produce an adapter that will make the rival duopolist's complementary component compatible. Like Matutes and Regibeau, he finds that the duopolists have a clear incentive to make the adapter as cheap as possible, a result that seems to suggest that the antitrust concerns of Adams and Brock (1982) are misplaced. As we discussed above and will see below, our model contrasts sharply in this respect.

Finally, David and Bunn (1988) discuss the role of converters in the dynamic adoption of technologies exhibiting network externalities. They argue that in the battle between rival technologies, the adoption process and its formation of *de facto* standards may be decisively tipped by the development of a "one-way" converter that allows one of the technologies to obtain some of the network externalities accruing from the installed base of the other, but not *vice versa* (see also Adams (1978)). David and Bunn illustrate their argument with an historical account of the battle between AC and DC electric supply systems.

Our paper is organized as follows. The model is described in Section 2. Sections 3 and 4 are respectively devoted to equilibrium and welfare under perfect competition. Monopoly is analyzed in section 5, and duopoly equilibrium and welfare are examined in Sections 6 and 7. Conclusions are presented in Section 8.

[18] The reason for this price effect is different from that in our model, however. In their model, when components are compatible, if a firm decreases the price of one of its components, demand for the rival's complementary component rises. With incompatible components, in contrast, if a firm drops its price it wins sales for its system at the expense of the rival. Thus incentives to decrease price are lower with compatibility.

2. A Model of Technology Adoption with Imperfect Converters

Each of many users chooses between two technologies, A and B, sold at prices p_A and p_B respectively. Users differ in their preferences for the two technologies but, because of network effects or other compatibility benefits, each is better off the more others are compatible. There are two means by which users (or, strictly, their products) can be compatible: the users may adopt the same technology, or they may adopt different technologies but achieve imperfect compatibility through converters.

Buyers' Preferences, Variety, and Compatibility

We consider a continuum of users, indexed by $s \in [0,1]$. A user's valuation of a technology has a "stand-alone" component (the benefit he derives if no others are compatible) and a "compatibility" component (the benefit he derives from others' compatibility). The stand-alone component for a user of type s is:

$$\begin{cases} a+s, & \text{if he adopts } A; \\ a+1-s, & \text{if he adopts } B. \end{cases}$$

Each user will adopt a single unit of one of the technologies (or else leave the market entirely). Users' relative preference for A over B increases in s and the constant a represents the value of the product independent of which technology is used.[19] Of particular interest are the users with the most extreme preferences: we call the user $s = 0$ the "B-lover": he derives a stand-alone benefit of 1 from B and 0 from A. An "A-lover," similarly, is the user of type $s = 1$.

Like much of the previous literature, we assume for simplicity that the "compatibility" or "network" component of utility is linear in the number (measure) of compatible users: this component of a user's utility is nx if a proportion x of all users adopt technologies compatible with his. His overall utility is then

$$\begin{cases} a+s+nx-p_A & \text{if he adopts A;} \\ a+1-s+nx-p_B & \text{if he adopts B.} \end{cases}$$

We assume constant, equal (and, for simplicity, zero) marginal costs of producing A and B.

We have assumed that the benefits of compatibility are identical for all buyers. Hence, if any buyer of a particular technology wishes to buy a converter, they all do. Despite the complete symmetry of the model, however, any (pure strategy) conversion equilibrium is *asymmetric*: one of

[19] The variable a plays a purely technical role: we suppose that a is sufficiently large so that all users buy one of the products at the equilibrium prices. Of course, the size-of-market externalities and related market-structure issues that we thus ignore may be important, but we think that they are not the most interesting aspects of the problem.

the technologies emerges as "dominant." To see why, imagine that the technologies were adopted almost equally but the users on one of them — say, B — were thought more likely to adopt converters. Then a user $s \approx \frac{1}{2}$ would have an incentive to buy A: he thus gets part of the compatibility benefits from the B-users (because converters are "two-way") and saves the price of the converter. And of course, once A thus gains more than a 50% market share, those who buy A have even less reason to buy converters, while those who buy B have all the more incentive to do so, in order to be compatible with the many users of the (perhaps endogenously) "dominant" technology A.

We suppose, as discussed in the Introduction, that converters are imperfect and create only a fraction $1 - q$ of the "full" compatibility benefits. The "imperfection" $q \geq 0$ reflects converters' inconvenience in use, the performance degradation that so often accompanies conversion, and the fact that complementary goods (such as software) are typically designed for the main market, not for use by those with converters. Thus, an A-user who buys a converter gets a fraction $1 - q$ of the compatibility benefit that he would get from the B-users if they all adopted A instead — in addition, of course, to the compatibility benefit he derives from the other A-users. Because we chose to model symmetric two-way converters, moreover, he confers the same fraction $1 - q$ of his full potential compatibility external benefits on the B-users. Thus, if a fraction s of users adopt B and a fraction $1 - s$ adopt A, a B-user who buys a converter gets a compatibility benefit of $n[s + (1 - q)(1 - s)]$. If all B-users buy converters, then each A-user gets a compatibility benefit of $n[1 - s + (1 - q)s]$.

3. Equilibrium With Perfect Competition

With perfect competition (unsponsored technologies), prices are equal to marginal costs of production: thus $p_A = p_B = 0$ and $p_C = c$, where c is the production cost of converters. Our focus is therefore on users' choices between the technologies and on who, if anyone, buys converters.

Three types of (pure-strategy) equilibrium are possible. We can have *standardization*: everyone chooses the same technology, and is thus perfectly compatible. We can have the opposite, *incompatibility*, in which half of the users choose technology A and the other half choose B, and nobody buys a converter: thus users follow their preferences but sacrifice compatibility. Finally, we can have a compromise solution: *conversion*, in which users buy different products and — imperfectly and at a cost — achieve compatibility through converters. In this section, we find conditions under which each of these is an equilibrium. In the next, we will discuss welfare issues in these equilibria.

Standardization

When is it an equilibrium for all buyers to buy the same technology, say A?[20] Suppose it were expected that everyone would buy technology A. The buyer most tempted to deviate is the buyer $s = 0$: the "B-lover". He might defect either by simply buying technology B instead of A, or he might also buy a converter. The conditions that he should wish to do neither are $n \geq 1$ and $n \geq 1 - c + (1-q)n$, respectively. Consequently, standardization is an equilibrium if and only if

$$n \geq 1 \quad \text{and} \quad nq + c \geq 1. \tag{1}$$

Incompatibility

In any "incompatibility" equilibrium, buyers with $s > \frac{1}{2}$ buy A, while those with $s < \frac{1}{2}$ buy B. For clearly there must be a cutoff (the users who choose A must be those with the large values of s), and the cutoff σ must satisfy $(1-\sigma) + n\sigma = \sigma + n(1-\sigma)$, whence $\sigma = \frac{1}{2}$ (at least for $n \neq 1$).[21]

When is this an equilibrium? Strictly, there is no incentive for any user to defect to the other technology: the user $s = \frac{1}{2}$ is indifferent, and all others are using their preferred technology, while the network benefits on each are identical. However, if $n > 1$ then the equilibrium is unstable in the following sense. Suppose that a fraction $\sigma > \frac{1}{2}$ of buyers were expected to buy technology B, with the others buying A. Then (given those expectations) *more* than σ of all buyers would in fact choose B, and so the incompatibility equilibrium is unstable.[22] Therefore a necessary condition for a "reasonable" incompatibility equilibrium is that $n \leq 1$. The condition that there be no incentive to defect by buying a converter is simply that the cost, c, should at least equal the additional compatibility benefits that the buyer derives from the converter: $c \geq \frac{1}{2}(1-q)n$. Thus incompatibility is an equilibrium if and only if

$$n \leq 1 \quad \text{and} \quad nq + 2c \geq n. \tag{2}$$

[20] With the symmetric preferences we assume, the condition for it to be an equilibrium for all to buy B instead will be the same.

[21] When $n = 1$ the cutoff equation tells us nothing, so there are many incompatibility equilibria.

[22] Also, with a finite number y of users (the continuum is an approximation to this reality), if $n > 1 + \frac{1}{y}$ then there is no incompatibility equilibrium at all.

Conversion

Finally, when is it an equilibrium for some buyers to buy each technology, and for some to buy converters? With the consumer preferences that we assumed, if one buyer on technology A (say) finds it worth buying a converter, then so does every other. Therefore in a pure strategy conversion equilibrium either all the A-users or all the B-users buy converters. In the former case the A-users are free-riding off the B-users, and conversely in the latter case.

The users therefore face a coordination problem: which group is expected to buy the converter? In our model, there is no clue available to break the symmetry between technologies A and B, and one might argue that a failure of coordination is likely. One might usefully explore the economics of such coordination failures; or one might examine the factors (expectations, history, and the like) that might break the symmetry. Here, however, we will take a different approach, and suppose that the coordination problem *is* somehow solved. Without loss of generality, we suppose that it is the B-users who get stuck with the cost and with the consequently smaller network.

When the B-users are expected to bear the direct costs of conversion, the cutoff point will not be at $s = \frac{1}{2}$: a buyer near $s = \frac{1}{2}$ will prefer to buy technology A, since he can then free-ride on the B-users' provision of converters. Consequently, more than half the users will choose A (and this makes A all the more attractive). Thus A emerges as a "dominant technology" in equilibrium. In fact, the equilibrium cutoff, s^*, that divides the B-users from the A-users is given by

$$s^* + n(1 - s^*) + n(1 - q)s^* = 1 - s^* + ns^* + (1 - q)n(1 - s^*) - c,$$

or

$$s^* = \frac{1}{2} - \frac{c}{2(1 - nq)}. \tag{3}$$

As we show below, existence of a conversion equilibrium requires that $nq < 1$.[23] Therefore if $c > 0$ then $s^* < \frac{1}{2}$. We find "tipping" ($s^* \neq \frac{1}{2}$) despite the complete symmetry of the model and the absence of symmetry-breaking random factors as in Arthur (1989): there is not even an *unstable* symmetric conversion equilibrium in pure strategies.[24] Not surprisingly, the tipping is

[23] Moreover, if $nq > 1$ then the cutoff equilibrium is unstable. To see why, consider what happens if the B-users switch *en masse* to A. A user located at s loses $(a + 1 - s) - (a + s) = 1 - 2s$ in stand-alone benefits, but gains $1 - [s^* + (1 - q)(1 - s^*)] = nq(1 - s^*)$ in network benefits. Therefore if $nq > 1$ then all the B-users (including the extreme B-lover) would prefer A if every user with a higher s adopted A.

[24] Of course, since the game is symmetric, there is a symmetric equilibrium, and this may involve converters, in which case it requires mixed strategies. We will focus on the asymmetric pure-strategy conversion equilibrium, however: it is more efficient, and our purpose is at least in part to evaluate the claim that conversion is likely to be an efficient way to achieve compatibility.

more pronounced the larger is c, and the larger is the compatibility benefit disadvantage of the minority group, measured by the product of n, the importance of network benefits, and q, the imperfection of conversion.

For a conversion equilibrium to exist, s^* must be between 0 and 1: that is, $0 < 1 - nq - c < 2(1 - nq)$, or $nq + c < 1$. And a B-buyer must find it worth buying a converter, given the market shares of the two technologies: $c \leq n(1 - q)(1 - s^*)$. Thus there is a conversion equilibrium if and only if

$$qn + c < 1 \quad \text{and} \quad c \leq \frac{n(1 - q)(1 - nq)}{2 - n - nq}. \tag{4}$$

Any such equilibrium is characterized by a cutoff point s^* given by (3) if the B-users buy the converters (and by (3) with c replaced by $-c$ if the A-users do so).

Summary of Equilibrium

In Figure 1 we plot n on the horizontal axis and c on the vertical. We show the regions in which the various types of equilibria occur; this requires us to plot the curves $n = 1$, $nq + c = 1$, $nq + 2c = n$, and $c = \frac{n(1-q)(1-nq)}{2-n-nq}$. As the figure illustrates, there are regions in which conversion, standardization, and incompatibility are the unique[25] equilibrium outcomes. There is also a region in which both a conversion equilibrium and an incompatibility equilibrium exist. These results are summarized as:

Proposition 1. *A pure-strategy equilibrium always exists, and is qualitatively unique except that for some parameter values both an incompatibility equilibrium and a conversion equilibrium exist.*

Converters are adopted in equilibrium when they are inexpensive (c small) or highly efficient (q small), and/or when network externalities are "moderate" ($n \approx 1$). When network externalities

[25] Throughout the paper, we will ignore mixed-strategy equilibria, and will also ignore the non-uniqueness caused by the fact that, for instance, if standardization on A is an equilibrium then so is standardization on B, and likewise if conversion with A dominant is an equilibrium then so is conversion with B dominant.

While competitive *firms* do not care what equilibrium arises (they make zero profits in any case), *users* care. In a conversion equilibrium in which A is the dominant technology, the B-lovers are unambiguously worse-off than the A-lovers: they not only have to buy converters but also have smaller network benefits (they are perfectly compatible only with the minority group, and only imperfectly compatible with the majority).

Although this is not part of our model, one can speculate on the factors that lead to one technology or the other becoming dominant. Perhaps the most obvious is if (say) technology A has long been the only one available. When technology B is first introduced, it appeals strongly to a few unattached users: perhaps strongly enough that they disrupt the standardization equilibrium (as described above), but initially it is very natural that they (if anyone) should buy converters. In this way an equilibrium may be set up in which B-users buy converters, and this equilibrium may persist long after any physical capital stock that originally embodied A's installed base advantage has rusted away.

If no such symmetry-splitting factors are present, it is by no means clear how "the market" can choose an asymmetric conversion equilibrium. In this context, we note that the incompatibility equilibrium, if it exists, is symmetric. Thus, if there is no mechanism coordinating users on one or the other conversion equilibrium, the incompatibility equilibrium may be more likely to arise when both exist.

are small, conversion is unimportant, because incompatibility is not costly and users are unwilling to pay c for conversion. When network externalities are large, on the other hand, conversion is unimportant because users are not willing to bear the partial incompatibility costs associated with the imperfection (q) of converters.

When $n < 1$, converters increase compatibility; they replace incompatibility with (imperfect) conversion. But when $n > 1$, they decrease compatibility: they replace standardization with imperfect compatibility. Thus, they are a force for compatibility when it is not very important, but a force against it when it matters!

The dividing line between incompatibility and standardization is determined solely by the magnitude of n (in particular whether $n > 1$). This is because if $n < 1$ the B-lover deviates from a standardization equilibrium, preferring the stand-alone benefit of 1 to the network benefit of n.

The boundary between conversion and standardization depends on both n and c: Conversion will emerge as long as c is small relative to n. The intuition for this is that if n is large, imperfect conversion, which provides only a fraction of the network externalities, is relatively unattractive compared to standardization. Thus in order for conversion to emerge the cost of conversion must be lower the larger is n. Notice in particular that if $q = 0$ (so that conversion is perfect), the dividing line between conversion and standardization is horizontal: standardization gives way to conversion as the equilibrium when converters are inexpensive.

The possibility of multiple equilibria is easy to understand. Because the group (the B-buyers) expected to buy converters is a minority, and because converters are more valuable to you if your group is smaller (the other group is larger), it can easily be the case that a converter is worth buying if your group was expected to buy converters, but not if nobody was expected to (so that the groups were of equal sizes).

4. Welfare With Perfect Competition

In this question we compare welfare across equilibria, with the goal of understanding any market biases. We find that standardization is too seldom an equilibrium, and that converters are used too much.

Standardization versus Variety — Without Converters

While our primary focus is on conversion, it is interesting to compare incompatibility and standardization, without converters. In our model, this amounts to comparing the benefits of variety with those of compatibility when the latter can be achieved only by foregoing variety and standardizing.

Since network externalities create an economy of scale on the demand side, this problem is much like the familiar trade-off between variety and production economies of scale.

First, in a standardization equilibrium, the buyer of type s gets stand-alone benefit $a+s$ and network benefit n, because everyone is compatible. Thus, total welfare is

$$W^S = \int_0^1 [a+s+n]ds = a + \frac{1}{2} + n. \tag{5}$$

Second, in an incompatibility equilibrium, the buyer of type s gets stand-alone benefit $\max(a+s, a+1-s)$ and network benefit $\frac{n}{2}$. Thus, welfare is

$$W^I = 2\int_{\frac{1}{2}}^1 [a+s+\frac{1}{2}n]ds = a + \frac{3}{4} + \frac{1}{2}n. \tag{6}$$

From (5) and (6), standardization is preferable to incompatibility if and only if $n > \frac{1}{2}$. But, as we saw above, standardization is only an equilibrium when $n \geq 1$. Thus there is a bias towards incompatibility: for $\frac{1}{2} < n < 1$, the market chooses incompatibility rather than the superior standardization. Intuitively, standardization is blocked by the B-lover's strong preference for B: he enforces incompatibility, and this harms those users who favor A and those, near $s = \frac{1}{2}$, who do not much care between A and B but would welcome an arbitrary standard.[26]

Proposition 2. *When converters are unavailable, or costly enough that conversion is not an equilibrium, there is a bias towards incompatibility and away from standardization.*

Welfare Effects of Converters

In the remainder of this section we evaluate the welfare effects of converters. First, assuming that conversion occurs, we examine whether the equilibrium cutoff is optimal. Second, we ask whether equilibrium conversion occurs when it is socially optimal, *i.e.*, do we get conversion rather than incompatibility or standardization when we should?

[26] In Farrell and Saloner (1986b), we considered a model with just two types of user: A-types and B-types. In that model, we showed (Proposition 6) that standardization, when it is the unique equilibrium, is necessarily efficient. For if a defection by some users from A to B is socially desirable in terms of aggregate payoff, then it surely is privately profitable for those buyers in aggregate (if they can coordinate their defection), since the impact on the remaining A-buyers is negative. With just two types of buyers, if such a group defection is favorable for a group of type-B's in aggregate then it is favorable for all members of the group. Consequently, there must be another equilibrium in which the B-types choose B (this might be standardization on B or it might be incompatibility), and standardization on A was not after all the unique equilibrium. But in our present model, with more types, nothing guarantees that the *marginal* member of a group of users who, on aggregate, gain by defecting to B, gains from the defection. So this result is not a corollary of our previous one.

We take up these two issues respectively in the following subsections. We find that, despite perfect competition, in neither respect is the outcome efficient. With the linear network benefits that we assume, when conversion does occur, too few users buy the dominant technology (A) and too many users buy B and a converter. And in comparing conversion to standardization, the availability of converters may lead to a conversion equilibrium when standardization would be better: Converters can actually make matters worse!

Equilibrium and Optimal Conversion Cutoff Compared

It is tempting to think that a user who buys a converter is "doing more for compatibility" than one who buys a product without a converter. This is right, of course, if we think of his buying the same product with or without a converter. But in a conversion equilibrium of the kind we consider, a marginal user chooses between buying B with a converter and buying A without. The relative contribution to compatibility is not obvious, and in general is ambiguous; in our model a user who adopts A confers a greater total externality on others than does one who adopts B and a converter. Thus too many people buy converters.

Suppose that network benefits to each user on a network of size x are $N(x)$, rather than the special form nx that we have assumed. Consider a conversion equilibrium in which A-users do not buy converters but B-users do. If a user of infinitesimal size ds adopts A, as do a fraction $1-s$ of the others, then he confers an externality of $N'(1-s+(1-q)s)\,ds$ on each of the $(1-s)$ A-users, and of $(1-q)N'(s+(1-q)(1-s))\,ds$ on each of the s B-users (who have converters). If instead he adopts B and buys a converter, he confers an externality of $(1-q)N'(1-s+(1-q)s)\,ds$ on each of the A-users and of $N'(s+(1-q)(1-s))\,ds$ on each of the B-users. It is simple to check that the externality from adopting A is greater than that from adopting B if and only if

$$\frac{N'(1-s+(1-q)s)}{N'(s+(1-q)(1-s))} > \frac{s}{1-s}.$$

But in equilibrium $s < \frac{1}{2}$, so this condition holds if $N(\cdot)$ is linear (as we have assumed) or convex. If $N(\cdot)$ is sufficiently concave, however, we would have the opposite case. This is not surprising: the extreme form of a concave $N(\cdot)$ is a threshold function which (almost) stops rising after a certain threshold network size is attained. With such an $N(\cdot)$, it is clear that it is at least sometimes socially better to join the smaller network.

For what follows it is useful to derive the optimal conversion cutoff. We can write the welfare from conversion with a cutoff of s as:

$$W^C(s) = a + n + \frac{1}{2} + (1-2nq)s(1-s) - cs. \tag{7}$$

Here, the total network benefit is the maximum possible, n, less an amount due to the converters' imperfections: there is a loss of $qs(1-s)n$ because the s B-users get a fraction q less benefit than they might from the $1-s$ A-users, and an equal total loss is borne by the A-users. Thus the lost network benefits are $2nqs(1-s)$. The stand-alone benefits are $\int_0^s [a+1-t]dt + \int_s^1 [a+t]dt = a + \frac{1}{2} + s(1-s)$. Finally, the direct cost of the converters is cs.

From (7), the first-order condition for the optimal cutoff $\hat{s}$ is

$$-2nq + 4nq\hat{s} - 2\hat{s} + 1 - c = 0,$$

or

$$\hat{s} = \frac{1}{2} - \frac{c}{2(1-2nq)}. \tag{8}$$

Comparing (8) and (3) confirms that $s^* > \hat{s}$.

Proposition 3. *Provided the parameters c, q, and n are all strictly positive, too many users join the minority group and buy converters: $s^* > \hat{s}$. However, this result depends on the assumption that network benefits are linear.*

Welfare in the optimal conversion outcome (which is typically not an equilibrium) is:

$$W^C(\hat{s}) = a + n + \frac{1}{2} + \frac{(1-2nq-c)^2}{4(1-2nq)}, \tag{9}$$

and the formula for $W^C(s^*)$ (substituting (3) in (7)) is:

$$W^C(s^*) = n + \frac{1}{2} + \frac{1-nq-c}{4(1-nq)^2}\Big((1-2nq)(1-nq) - c\Big). \tag{10}$$

Welfare Comparisons of Equilibrium Conversion, Standardization, and Incompatibility

Standardization is preferable to optimal conversion if $c > 1 - 2nq$. This is a necessary condition for $\hat{s}$ to be positive in (8).[27] Comparing (5) and (10), we see that equilibrium conversion is preferred to standardization if and only if $(1-nq)(1-2nq) > c$. The curves $c = 1-2nq$ and $c = (1-nq)(1-2nq)$ are drawn in Figure 2.

In the single-and double-shaded areas conversion occurs in equilibrium but standardization would be better. In the double-shaded area the conversion equilibrium is worse only because the equilibrium conversion cutoff is not optimal (Proposition 3); *optimal* conversion would be better than standardization. But in the single-shaded area, even optimal conversion would be worse than standardization: it would be better to ban converters!

[27] More formally, note from (7), that $W^C(s)$ is concave in s if and only if $nq < \frac{1}{2}$. Therefore if $0 < c < 1 - 2nq$, $W^C(s)$ is concave and has an interior (conversion) optimum. If $0 < 1 - 2nq < c$, $W^C(s)$ is concave but has the boundary solution $\hat{s} = 0$: standardization is optimal. If $0 < 1 - 2nq$, then $W^C(s)$ is convex in s, and again standardization is better than conversion.

Proposition 4. *In some cases, the equilibrium use of converters is socially preferable to standardization. In others, standardization would be better than the equilibrium use of converters, but a judicious use of converters would be better still. And in other cases, standardization is socially preferable even to optimal conversion, even though conversion is the unique equilibrium outcome.*

Comparing (10) and (6), conversion is preferable to incompatibility provided $c^2 - 2c(1 - nq)^2 + 2n(1-q)(1-nq)^2 > 0$. It is straightforward to show that this condition holds when $c = \frac{n(1-q)(1-nq)}{2-n-nq}$; thus,

Proposition 5. *Whenever conversion is an equilibrium it is preferable to incompatibility; but incompatibility is sometimes the equilibrium when conversion is preferred.*

Notice that users who adopt A in both regimes benefit from imperfect compatibility with the B-adopters under conversion, but that the "swing" adopters (those who adopt B under incompatibility but A under conversion) end up with a technology from which they derive lower stand-alone benefits. An additional affect is that the swing adopters shift from being perfectly compatible with the B-adopters to being perfectly compatible with the A-adopters. Because we have assumed that network benefits are linear, the gain of each A adopter is exactly equal to the loss of each B-adopter. Since there are more A-adopters in equilibrium this effect is positive. In general, however, with decreasing marginal benefits to expanding the network, the loss to the B-adopters could outweigh the gain to the A-adopters. Thus this proposition, too, depends on linearity of the network benefits.

Thus, in our linear model, there is too much incentive to adopt a minority technology and soften the loss of network benefits by buying a converter. At the same time, there is too little incentive to buy a converter, given that one is adopting a minority technology.

5. Monopoly

As we have seen, under perfect competition the availability of imperfect two-way converters fails to solve the problem of the adoption externality: there remains a network externality problem.

When a single firm controls the prices of A, B, and the converter, it can internalize these externalities. In fact, it is easy to see that the monopolist can implement the first-best outcome by suitably setting the prices of A, of B with a converter, and of B without a converter. But this may not maximize the monopolist's profits, since it cannot extract all the surplus from users. Rather, it chooses its policies to please the *marginal* buyers. To the extent that their preferences differ from the inframarginal buyers', the resulting outcome may be inefficient. We focus on this

distortion and ignore the possible reduction in total market size (due to above-cost pricing), by examining the case where the parameter a is large enough that in equilibrium the entire market is served. Our main interest is in whether the monopolist correctly "chooses" between standardization, incompatibility, and conversion equilibria — that is, chooses prices that cause buyers to standardize, to be incompatible, or to engage in conversion.

Monopolist's Choice Between Standardization and Incompatibility

Consider first the choice between standardization and incompatibility. If the monopolist chooses not to provide a converter when it sells B, it chooses s_M to maximize $(a+1-s_M)p_A + s_M p_B$, setting $p_A = a + s_M + (1-s_M)n$ and $p_B = a+1-s_M+ns_M$. This gives $s_M^* = \frac{1}{2}$ with $p_A = p_B = a + \frac{n+1}{2}$ if $n < 1$ and $s_M = 0$ with $p_A = a+n$ if $n \geq 1$; *i.e.*, if the monopolist does not provide a converter then users standardize if $n \geq 1$ and choose incompatibility otherwise. Recall that from a welfare standpoint, in the absence of conversion, standardization is preferable to incompatibility if $n > \frac{1}{2}$. Thus for $\frac{1}{2} < n < 1$ the monopolist, like the perfectly competitive market, provides incompatibility when standardization is preferable.

The reason the monopolist does not implement the social optimum is somewhat different from that for the competitive market. In order to implement standardization the monopolist must charge a price that induces the B-lover to buy A. The monopolist has the advantage over the competitive market that it can refuse to supply B, or make it prohibitively costly, so it is not constrained in its pricing of A by the B-lover's temptation to switch to B. It must, nonetheless, price A so that the B-lover prefers buying A to staying out of the market altogether: thus it can charge no more than $a+n$. If it chooses incompatibility, however, then the marginal buyer is no longer the B-lover, but is the buyer at $s = \frac{1}{2}$; thus the monopolist can charge $a + \frac{n}{2} + \frac{1}{2}$. The extra $\frac{1}{2}$ that it can extract in stand-alone benefits makes incompatibility more profitable as long as $\frac{1}{2}$ exceeds the $\frac{n}{2}$ it forgoes in network benefits: The monopolist therefore chooses incompatibility unless $n > 1$.

We next consider the monopolist's choice of conversion versus standardization or incompatibility. As a first step, we must ask what will happen if it chooses conversion.

We consider a monopolist charging a price p_A for good A, a price p_{BC} for a unit of good B with a converter when it chooses to provide a converter, and a price p_B for B alone when it chooses incompatibility. When the monopolist chooses to sell the converter (and satisfy the entire market), its prices must satisfy:

$$\begin{aligned} p_A &= a + s_M + n(1-s_M) + n(1-q)s_M, \quad \text{and} \\ p_{BC} &= a + 1 - s_M + ns_M + (1-s_M)(1-q)n. \end{aligned} \tag{11}$$

where $s_M = \frac{1}{2} - \frac{p_{BC} - p_A}{2(1-nq)}$ is the monopoly cutoff.

The monopolist maximizes $s_M(p_{BC} - c) + (1 - s_M)p_A$. Setting p_A and p_{BC} equal to the right-hand-sides of (11) and maximizing with respect to s_M yields:

$$s_M^* = \frac{1}{2} - \frac{c}{4(1-nq)}. \tag{12}$$

Substituting (12) in (11), we find that monopoly profits are given by:

$$\pi^M = n + \left(\frac{1}{2} - \frac{c}{4(1-nq)}\right)^2 \left(\frac{1-nq}{2}\right).$$

(Notice that π^M is decreasing in both q and c.) Hence, the monopoly prices are:

$$\begin{cases} p_A^* = a + n + (1 - nq - c/2)/2, & \text{and} \\ p_B^* = a + n + (1 - nq + c/2)/2. \end{cases}$$

Proposition 6. *The conversion cutoff under monopoly is even higher than under competition.*

Now consider the monopolist's choice of standardization versus conversion. The monopolist chooses standardization if the conversion cutoff (12) is nonpositive, *i.e.*, if $c \geq 2(1 - qn)$. Recall that under perfect competition standardization emerges only if $c \geq 1 - qn$, so that the monopolist favors conversion over standardization more than does the competitive market. Since even the competitive market sometimes produces conversion even when standardization is preferable, the monopolist exacerbates this distortion as well.

To understand this result, note that if it were offering only A, the monopolist would have to set a rather low price in order to induce the B-lover to buy. The monopolist can often do better by raising the price of A above the B-lover's willingness to pay (even with the maximum network), and extracting more surplus from the inframarginal A-buyers. The monopolist can then "pick up" the lost buyers located near $s = 0$ by offering B (bundled with the converter) and pricing it appropriately.

The monopolist is also more likely than the competitive market to prefer the conversion outcome to incompatibility. In particular, it is straightforward though tedious to show that for $n < 1$, whenever conversion is an equilibrium under perfect competition (even if there are also other equilibria), it is also the monopoly equilibrium.[28]

[28] In the conversion equilibrium profits are equal to $p_A^*(1 - s_M^*) + (p_{BC}^* - c)s_M^*$. Substituting (12) and (11) into this expression gives $a + n + \frac{1-nq}{\ } \frac{c}{\ } + \frac{c}{-nq}$. Since profits from incompatibility are given by $a + \frac{n}{\ }$, profits from conversion are higher if $4(1 - nq)(n(1 - q) - c) + c \geq 0$. A sufficient condition for conversion profits to be higher is therefore that $n(1 - q) > c$. Recall that the point at which conversion ceases to be an equilibrium under perfect competition is $c = \frac{n-q-nq}{-n-nq}$. Therefore there exists a region in which conversion is more profitable than incompatibility for the monopolist but not an equilibrium under perfect competition if $n(1 - q) > \frac{n-q-nq}{-n-nq}$. Since $1 - nq < 2 - n - nq$, such a region exists.

Recall that the competitive market sometimes results in incompatibility when conversion is preferable (Proposition 5). While monopoly is more likely to give conversion than is perfect competition, even the monopolist sometimes chooses incompatibility when conversion would be preferable.[29] The reason can again be traced to the monopolist's inability to capture the rents of the inframarginal buyers. While conversion creates value to all buyers, the monopolist is constrained in its pricing by the marginal buyer's reservation price. It cannot appropriate the full gains in compatibility benefits stemming from conversion that accrue to the inframarginal buyers, without losing some marginal buyers.

6. Equilibrium With Duopoly

We now examine a duopolistic market structure in which technologies A and B are proprietary to firms A and B respectively. We suppose that the firms simultaneously set their prices p_A and p_B and that users, knowing these prices and the price of the converter (initially assumed to be competitively supplied at $p_C = c$), then simultaneously make their adoption decisions.

As above, standardization, incompatibility, and conversion equilibria can arise, and multiple equilibria are possible. Here, however, we must recognize that consumers' beliefs may depend on the prices they face. For example, consumers might believe that if standardization occurs at all, it will occur on the less costly alternative. Alternatively, one of the products might be "focal": consumers may expect that it will be adopted even if it is the more expensive product. Such beliefs are plausible, for example, if one of the products is produced by a firm that has historically been dominant in the industry. As we shall see below, conversion equilibria are typically of this "dominant firm" type. Accordingly we make these equilibria the focus of our analysis and briefly comment on other equilibria below.

Duopoly Conversion Equilibrium

Suppose that product A is "dominant" so that it is expected that the B-buyers will buy converters. Then the user located at s_D is indifferent between the technologies if:

$$a + 1 - s_D + ns_D + (1-q)(1-s_D)n - p_B - c = a + s_D + n(1-s_D) + (1-q)s_D n - p_A,$$

[29] To see this, recall that conversion is preferable to incompatibility if and only if $c^2 - 2c(1-nq)^2 + 2n(1-nq)^2(1-q) \geq 0$ but that (from the previous footnote), the monopolist chooses conversion over incompatibility if and only if $c^2 - 4c(1-nq) + 4n(1-nq)(1-q) \geq 0$. To see that the first expression continues to hold when the second no longer does, note that the latter holds with equality when $2n(1-q)(1-nq)^2 = 2c(1-nq)^2 - c^2\frac{1-nq)^2}{2}$. Substituting this in the former yields $c^2 - c^2\frac{1-nq}{2} > 0$.

where the subscript D denotes duopoly. Firm B's sales are given by:

$$s_D = \frac{1}{2} - \frac{(c - p_A + p_B)}{2(1 - nq)}. \tag{13}$$

Now we can solve for the noncooperative equilibrium in prices simply by writing the first-order conditions

$$\begin{cases} 0 = \frac{\partial}{\partial p_A}[p_A(1 - s_D)] = 1 - s_D - \frac{p_A}{2(1-nq)} & \text{for } A; \\ 0 = \frac{\partial}{\partial p_B}[p_B s_D] = s_D - \frac{p_B}{2(1-nq)} & \text{for } B. \end{cases} \tag{14}$$

Solving these equations gives

$$\begin{cases} p_A = 1 - nq + c/3; \\ p_B = 1 - nq - c/3, \end{cases} \tag{15}$$

so the equilibrium conversion cutoff is given by:

$$s_D^* = \frac{1}{2} - \frac{c}{6(1 - nq)}. \tag{16}$$

Proposition 7. *The technology whose buyers are expected to buy converters commands the smaller market share and the lower equilibrium price.*

Two things are worth noting about equations (15). First, p_A is increasing in c, so in equilibrium A-buyers pay some of the cost of conversion. Second, it is often suggested that compatibility sharpens price competition, because it reduces "buyer lock-in", whose adverse effects on price competition are well known.[30] Here, however, incompatibility increases price competition and thus leads to lower prices: both prices are *decreasing* in q, our measure of the imperfection of conversion. Thus the better the converters, the higher the prices, contrary to the common intuition. The reason is that when the converters are close to perfect, buyers obtain (approximately) the same network benefits regardless of which product they buy. Their choice of product then depends more on stand-alone benefits the product has to offer and product differentiation becomes relatively more important, and so a seller gains less in sales by a given price cut.

Proposition 8. *The possibility of conversion blunts competition and leads to higher prices.*

The equilibrium cutoff s_D^* exceeds that in either the competitive or monopoly cases. Thus a conversion equilibrium with duopoly is more "equitable" than either a conversion equilibrium with proprietary products or where both products are proprietary to the same firm: the networks are of more equal sizes and, moreover, the difference in total per capita expenditures between B-buyers and A-buyers is only $c/3$ instead of $c/2$ in the case of monopoly or c for competition. The

[30] See for instance Klemperer (1987) and Farrell and Shapiro (1988).

difference between the duopoly and competitive cases, as remarked above, is that the duopolist A raises its own price in response to the higher costs faced by a buyer who contemplates buying B. To compare the duopolists' incentives to those of the monopolist, consider the monopolist starting at the duopoly outcome. By raising the price of A relative to B it can save on converter costs. Duopolist A, in contrast, ignores this externality on duopolist B.

The calculations in this subsection apply only so long as (16) is between 0 and 1 and B-buyers find it worth while to buy a converter. Condition (16) requires $c \leq 3(1-nq)$. The condition that B-buyers do not want to stay on B and refuse to buy a converter is that $c \leq (1-q)n(1-s^*)$, or

$$c \leq \frac{3(1-q)n(1-nq)}{6-n-5nq}. \tag{17}$$

Duopoly Standardization Equilibrium

We focus on the case where A is focal in that consumers all believe that others will buy A if such an outcome is sustainable as an equilibrium. This may occur, for example, where a firm that has held the position of *de facto* standard-setter for the industry in previous generations of products is the "focal" supplier in succeeding generations. For this case, it is straightforward though tedious (see the Appendix) to check that a "dominant firm" standardization equilibrium exists if $n > 1$ and $c > \min\{n(1-q), 3(1-nq)\}$. In equilibrium $p_B = 0$, while $p_A = n-1$ if $c > n(1-q)$, and $p_A = nq + c - 1$ if $n(1-q) > c > 3(1-nq)$.

Thus, standardization emerges over conversion only if $c > 3(1-nq)$, while the corresponding condition under monopoly is $c > 2(1-nq)$, and under perfect competition it is $c > 1-nq$. Thus conversion is more likely to take over from standardization under duopoly than under monopoly or perfect competition. A "fragmented" market is most likely with an intermediate market structure!

When the monopolist favors standardization it makes B unavailable. In contrast, in duopoly firm B stands ready to supply the B-lover at an arbitrarily low price; this is why standardization is less likely under duopoly than under monopoly. In comparison with perfect competition, on the other hand, standardization is less likely under duopoly because the duopolist A has an incentive to raise its price (above 0) even if in so doing it yields some market share to B.

Because standardization emerges over conversion in duopoly only when the converter is expensive, the temptation for the B-lover to defect from a standardization equilibrium without a converter becomes greater. Accordingly, as the proposition shows, in the duopoly case there is an additional constraint on the region in which standardization can exist.

Other standardization equilibria are sustainable if consumers believe that they will coordinate on the cheaper product if they coordinate at all. Such consumer beliefs create a "winner-takes-all" contest for the firms at the pricing stage. Bertrand competition will obtain and price will be driven down to zero (marginal cost). For an equilibrium of this kind to exist with standardization on A, it must be the case that the B-lover is not tempted to deviate and buy B, with or without a converter. The conditions for this are those given in (1).

Duopoly Incompatibility Equilibrium

For the user located at a cutoff s_D to be indifferent between A and B when no-one buys a converter requires that $a + 1 - s_D + ns_D - p_B = a + s_D + n(1 - s_D) - p_A$, or

$$s_D = \frac{1}{2} - \frac{(p_A - p_B)}{2(n-1)}. \tag{18}$$

Firm A's profit with this cutoff is $(1 - s_D)p_A$. Differentiating Firm A's profit with respect to p_A gives the first-order condition $2p_A - p_B + (n-1) = 0$, which, using symmetry, gives the equilibrium prices $p_A = 1 - n = p_B$. Thus if $n < 1$ symmetric incompatibility equilibria result in the firms making positive profits.

If $n > 1$ then incompatibility equilibria with $p_A = p_B = 0$ may exist which are unstable, as discussed above for the case of unsponsored technologies.

As in the perfectly competitive case, for an incompatibility equilibrium to exist, it must be the case that with an equilibrium cutoff of one-half, users do not want to buy converters. The condition for this is $c \geq \frac{(1-q)n}{2}$.

Summary of Duopoly Equilibrium

Figure 3, which is the duopoly analogue of Figure 1, illustrates the regions in which the various equilibria exist. (Where a curve has changed from its positions in the competitive case, its previous position is represented by short dashed lines). Consider first the region where $n < 1$. The region where incompatibility is an equilibrium is the same as under perfect competition. However, conversion is less likely than under perfect competition (which, in turn, is less likely than under monopoly). Thus the region of multiple equilibria is smaller under duopoly than in perfect competition. The reason that conversion is relatively unlikely under duopoly is that the equilibrium cutoff is larger here. Thus a B-buyer who defects by not buying a converter gives up less in lost network benefits.

Now consider the region where $n > 1$. As discussed above, standardization is a relatively less likely outcome than in the other regimes. Notice that a "new" region exists where there is no stable equilibrium. The intuition for why there exists neither a conversion nor a standardization equilibrium in this region is as follows. Given the prices that would prevail in a standardization equilibrium, the B-lover would deviate and buy a converter. This seems to suggest that a conversion equilibrium should exist. But at the prices that prevail in a conversion equilibrium, many users adopt B. Then, however, the benefits to purchasing a converter do not justify the high cost and no-one in fact is willing to buy a converter. This leaves the incompatibility equilibrium as the only candidate. Strictly, this unstable incompatibility equilibrium also exists for $n > 1$ as long as $c \geq \frac{1}{2}(1-q)n$. However, in the region where a standardization equilibrium also exists it is the more compelling equilibrium. Accordingly we have not represented the unstable incompatibility equilibrium there.

7. Welfare Under Duopoly

When there exists a conversion equilibrium in the duopoly, monopolistic, and perfectly competitive cases, the welfare comparison reduces to a comparison of the equilibrium conversion cutoffs in the respective cases. As noted above, the minority group is largest in the duopoly conversion equilibrium. Since too many users join the minority group and buy converters in the competitive case, we have:

Proposition 9. *The conversion cutoff is more biased under duopoly than under monopoly or perfect competition.*

Profit and Welfare Effects of c and q

From (16) and (15) the firms' profits are:

$$\begin{cases} \Pi_A = \frac{(1-nq+c/3)^2}{2(1-nq)}; \\ \Pi_B = \frac{(1-nq-c/3)^2}{2(1-nq)}. \end{cases} \tag{19}$$

Proposition 10. *Firm A has an incentive to make converters costly, as long as (17) holds. Firm B, on the other hand, would like them to be cheap.*

This result is intuitive and is consistent with frequent allegations[31] that dominant firms intentionally make conversion costly in order to preserve their full network-size advantage over their smaller rivals. As c increases, B becomes relatively less attractive and it becomes easier for firm A to attract marginal customers.

In our model, however, although the dominant firm wants converters to be expensive, both firms like converters to be as efficient as possible. This is because we assumed that converters are "two-way": whereas the cost of converters is borne only by the B users, a reduction in the quality of the converter affects the value of both technologies to all buyers. A simple calculation from (19) yields:

Proposition 11. *Both firms favor efficient converters.*

We turn now to an examination of buyers' welfare in the conversion equilibrium and how it is affected by changes in q and c. Buyers' welfare is as in Equation (7) except that buyers pay for the good they buy according to Equation (15). The total amount that buyers pay is given by

$$s_D^*(p_B + c) + (1 - s_D^*)p_A = \frac{s_D^* c}{3} + \{1 - nq + \frac{c}{3}\},$$

so that aggregate buyer welfare is given by:

$$W^P = n + \frac{1}{2} + (1 - 2nq)s_D^*(1 - s_D^*) - \frac{s_D^* c}{3} - (1 - nq + \frac{c}{3}). \tag{20}$$

Proposition 12. *In a conversion equilibrium, buyers' welfare is* increasing *in q.*

Proof. See Appendix. ∎

It turns out that the effect of c on buyer welfare is ambiguous; we spare the reader the details.

[31] Frequently, these allegations are made with respect to the dominant firm's refusal to allow the smaller firm (or new entrant) to join the dominant firm's larger (or existing) network. For example, Citicorp sued Western Union over the latter's alleged refusal to allow the former to use to its public money transfer network. Similarly, Automated Teller Machine Networks frequently denied access to competitors: "Until recently, the bylaws of many shared networks ... withheld access from members of competing networks." (Felgran (1985), p. 49).

Sponsorship of Converters

Because the cost of converters affects equilibrium duopoly profits in interesting ways, we next consider what happens if firm A, firm B, or a third party has proprietary control of the converter. This is of special interest because, in practice, converters are often supplied by vendors of the main product: for example, in word processing, WordPerfect bundles a partial converter with its product.

We examine the case where the price of the converter, p_C, is set at the same time as p_A and p_B. We examine the effects of such proprietary control of the converter on equilibrium and welfare. This is also a necessary first step in an analysis of who, if anyone, is likely to develop converters in a particular market.

(a) Firm B Controls Converter

If Firm B sells the converter it chooses p_B and p_C to maximize $s_D^*(p_B + p_C - c)$, where

$$s_D^* = \frac{1}{2} - \frac{p_C - p_A + p_B}{2(1-nq).} \tag{21}$$

Since p_B and p_C enter into the maximization in identical ways, we can think of Firm B as supplying a bundled product consisting of the primary product plus a converter at a price p_{BC} with a constant marginal cost of c. Rewriting (21), B chooses p_{BC} to maximize $(\frac{1}{2} - \frac{p_{BC}-p_A}{2(1-nq)})(p_{BC} - c)$, which gives the best-response function for B: $p_{BC} = (1 - nq + c + p_A)/2$. A's best-response function is $p_A = (1 - nq + p_{BC})/2$. Combining these equations gives the equilibrium prices:

$$\begin{cases} p_A = 1 - nq + c/3 \\ p_{BC} = 1 - nq - 2c/3. \end{cases} \tag{22}$$

The price for A and the "B package", and the final allocation of goods are as in the case when the converter is not sponsored: B's sponsorship of the converter has no effect on the equilibrium outcome. The reason is that control over the price of the converter does not give firm B an additional effective instrument. Any B buyer who buys a converter pays a total of $p_B + c$ when B does not control the price of the converter. Thus B can directly control the cost of the package as effectively simply by changing p_B.

Although the outcome is the same within the conversion region whether or not firm B controls the price of the converter, firm B's control of the converter can have important implications for equilibrium. Even if it does not change the combined price of B and the converter, it can manipulate their relative prices. Since the type of outcome that can be sustained depends on the price of the

converter, through this means Firm B can "choose" between conversion and incompatibility if $n < 1$.

Firm B's profits in the incompatibility and conversion equilibria are $\frac{1-n}{2}$ and $\frac{(1-nq-c/3)^2}{2(1-nq)}$ respectively. Thus conversion is more profitable provided $c^2 - 6c(1-nq) + 9n(1-nq)(1-n) > 0$. Recall that incompatibility can emerge as the equilibrium provided $c > \frac{n(1-q)}{2}$. Since conversion is more profitable than incompatibility when $c = \frac{n(1-q)}{2}$, there exists a region where incompatibility is an equilibrium but conversion — another equilibrium — is more profitable for firm B. In this region firm B can "select" the conversion outcome by pricing the converter low and B correspondingly high (perhaps actually bundling the converter with its product). In this sense, the minority (non-dominant) firm may be able to improve its competitive position by subsidizing or bundling a converter. It is interesting to note that this maneuver strictly reduces firm B's market share, but although its customers therefore derive a smaller network benefit from their "own" network, this is more than compensated by the partial network benefits derived through conversion.

Since conversion is better (from a welfare point of view) than incompatibility when they are both equilibria, this control of the converter by B can improve welfare.

(b) Firm A Controls Converter

When Firm A provides the converter, the analysis is very similar to that of the monopoly case. Indeed, given p_B, Firm A has the power to set the price of both A and the B-cum-converter option (through its price of p_C). Its pricing is constrained by how much it can charge without inducing the buyer located at s_D to refrain from purchasing at all. The maximum prices it can charge that are analogous to those in the monopoly case in Equation (11) are:

$$p_A = a + s_D + n(1-s_D) + n(1-q)s_D, \quad \text{and}$$
$$p_C = a + 1 - s_D + ns_D + (1-s_D)(1-q)n - p_B. \tag{23}$$

(23)*conprices*

where $s_D = \frac{1}{2} - \frac{p_C - p_A + p_B}{2(1-nq)}$ is the cutoff.

Substituting these values for p_A and p_C into its objective function, $p_A(1-s_D^*) + (p_C - c)s_D^*$ and maximizing with respect to s_D gives: $s_D = \frac{1}{2} + \frac{p_B - c}{2(1-nq)}$. (Note that setting $p_B = 0$ gives the same cutoff as in the monopoly case, as it should).

For its part, Firm B maximizes $p_B s_D$. Substituting for s_D and maximizing gives the optimal price for B of $p_B = \frac{c}{2} - (1-nq)$. Substituting this is the expression for s_D yeilds the equilibrium cutoff:

$$s_D^* = \frac{1}{4} - \frac{c}{8(1-nq)}. \tag{24}$$

(24)*off*

Notice that this cutoff is strictly lower than in the monopoly case. The intuition for this is straightforward. Firm A could implement the monopoly cutoff if it so desired. However, starting from that point, Firm A would have an incentive to lower the cutoff since any profit that is derived from buyers who purchases A it enjoys itself, whereas those that are derived from buyers who purchase B must be shared with Firm B. Since the cutoff is too high from a welfare point of view when the converter is unsponsored, Firm A's sponsorship of the converter can be welfare-improving: essentially through taxing its use.

(c) Third Party

A third party chooses p_C to maximize $(p_C - c)s_D^*$ with s_D^* given by (21), and subject to the constraint that B buyers are willing to buy the converter. When that constraint is not binding, the equilibrium prices are:

$$\begin{cases} p_A = (5(1-qn)+c)/4 \\ p_B = (3(1-qn)-c)/4 \\ p_C = 3(1-qn+c)/4, \end{cases}$$

and the equilibrium cutoff is given by:

$$s_D^* = \frac{3}{8} - \frac{c}{8(1-nq)}. \tag{25}$$

Compared to the unsponsored converter case, p_A is higher as is the total price paid by the B-buyers $(p_B + p_C)$. The equilibrium cutoff is always lower: Comparing (25) and (16), this is true provided $c < 3(1-nq)$, which is also the condition that $s_D^* \geq 0$ in both cases. Since the cutoff is too high from a social welfare point of view, the provision of converters by a third party can increase welfare. This is true only when c is fairly large, however. When c is zero, for example, the equilibrium and welfare optimal cutoffs coincide when the converter is not sponsored, but the cutoff is strictly too low (3/8 versus 1/2) when the converter is sponsored by a third party. As discussed above, when c is large, welfare can be increased by taxing the converter. Like firm A's sponsorship of the converter, third-party sponsorship has this effect.

8. Conclusion

The growing economics literature on compatibility and standardization has mostly assumed that compatibility is determined by product design alone and is all-or-nothing. In fact, some degree of compatibility can often be achieved *ex post* at a cost. We have analyzed some implications of this, focusing on the question of who buys converters.

As we discussed in the Introduction, converters might seem to promise compatibility without the variety-inhibiting straightjacket of standardization. Indeed, when converters are costless and perfect, this is true; but that is unfortunately rare. In general, the welfare impact of the availability of converters is ambiguous.

When network externalities are important, social welfare maximization typically requires that individuals not pursue their own tastes for variety as far as they would like. In the absence of converters, individuals' private and social incentives are not perfectly aligned, but some degree of social discipline is imposed by each individual's desire to get network externalities by doing what others wish to (and will) do. Converters, by lowering the private cost to an individual who disrupts the standards, can reduce welfare by making such disruption more likely — even though they also make it less disruptive.

In particular, when compatibility is important, but not supremely important, the availability of converters reduces the realized degree of compatibility. On the other hand, if compatibility is of only modest importance, incompatibility would result were there no converters. Then, converters can increase compatibility and social welfare.

Where one of the technologies is supplied by a firm with market power, our model suggests that that firm has an incentive to hinder its rival's attempts to achieve compatibility through converters. If a firm can make it costly for a user on a rival technology to achieve (even partial) compatibility with its own installed base, that makes the rival's technology more expensive, and its own relatively more attractive.

Appendix

Conditions for a Dominant Firm Standardization Equilibrium

Believing that all other users will buy A (even if it has a positive price) the B-lover will not be induced to buy B without a converter if $p_A - p_B \leq n-1$, or with a converter if $1+n(1-q)-p_B-c \leq n-p_A$, *i.e.*, if $p_A - p_B \leq nq+c-1$. The former (no converter) constraint is the binding one if $n-1 < nq+c-1$ *i.e.*, if $n(1-q) \leq c \equiv \hat{c}$.

Suppose, first, that $c < \hat{c}$. Then the standardization outcome is the limit of the conversion equilibrium as $s_D^* \to 0$. In such an equilibrium, firm B (which is indifferent over the possible prices it can charge) sets $p_B = 0$ so that it provides the greatest feasible constraint on A's pricing. A then charges as high a price as possible while still inducing the B-lover to buy from him: $p_A = nq+c-1$. For it to be the case that A does not prefer to charge a price which induces the B-lover to deviate and buy a converter, p_A must be at least as great as A's best-response to $p_B = 0$ in the conversion equilibrium. Using (14) and (13), A's best-response function is $p_A = \frac{1-nq+c+p_B}{2}$. Evaluated at $p_B = 0$, this means p_A must not exceed $\frac{1-nq+c}{2}$. Combining this expression with $p_A = nq+c-1$, yields the condition $c \geq 3(1-nq)$.

Finally, if $c > \hat{c}$, A can charge the highest price that does not induce the B-lover to switch to B without a converter, *i.e.*, $p_A = n-1$. Notice that as one moves from the region where incompatibility is the competing alternative to that in which conversion is, p_A (and hence firm A's profits) changes continuously. ∎

Proof of Proposition 12.

Converter degradation q affects buyer welfare in three ways: through equilibrium prices, through network benefits (holding s_D^* constant), and through the change in s_D^*. From (15) we see that $\partial p_A/\partial q = \partial p_B/\partial q = -n$: as q increases prices decrease at the rate n. On the other hand, the network benefit to a B-user (A-user) is $n[s_D^* + (1-q)(1-s_D^*)]$ ($n[1-s_D^* + (1-q)s_D^*]$) which decreases at the rate $(1-s_D^*)n$ (ns_D^*) as q increases. Since there are s_D^* B-users and $1-s_D^*$ A-users, the network benefits fall at the rate $2(1-s_D^*)s_D^* n$ as q increases. Thus the "price effect" outweighs the "network effect".

Therefore, apart from the effect of q on the equilibrium cutoff, buyers' welfare is increasing in q. As we now show, however, aggregate buyer welfare is maximized at a cutoff lower than that which pertains in equilibrium, except when $q = 0$ in which case the equilibrium and buyer welfare-maximizing cutoffs coincide exactly. Therefore, since an increase in q reduces the equilibrium cutoff, this effect can only increase buyer welfare.

From (20), buyer welfare (holding q constant) is maximized when

$$\frac{\partial W^P(s_D^*)}{\partial s_D^*} = (1 - 2nq)(1 - 2s_D^*) - \frac{c}{3} = 0,$$

i.e., where

$$\hat{s}_D^* = \frac{1}{2} - \frac{c}{6(1 - 2nq)}. \tag{26}$$

Comparing (16) and (26), $\hat{s}_D^* \leq s^*$, with equality holding when q is zero.

∎

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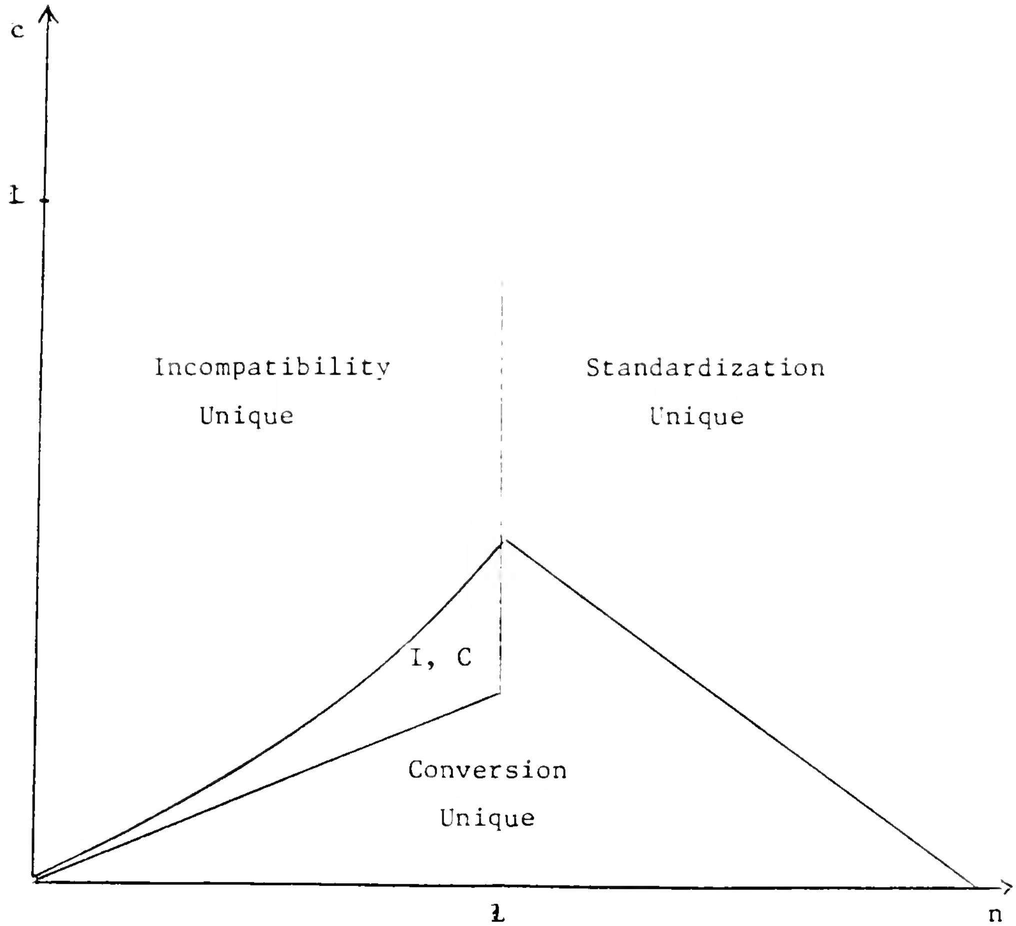

Figure 1: Equilibrium Outcomes Under Perfect Competition

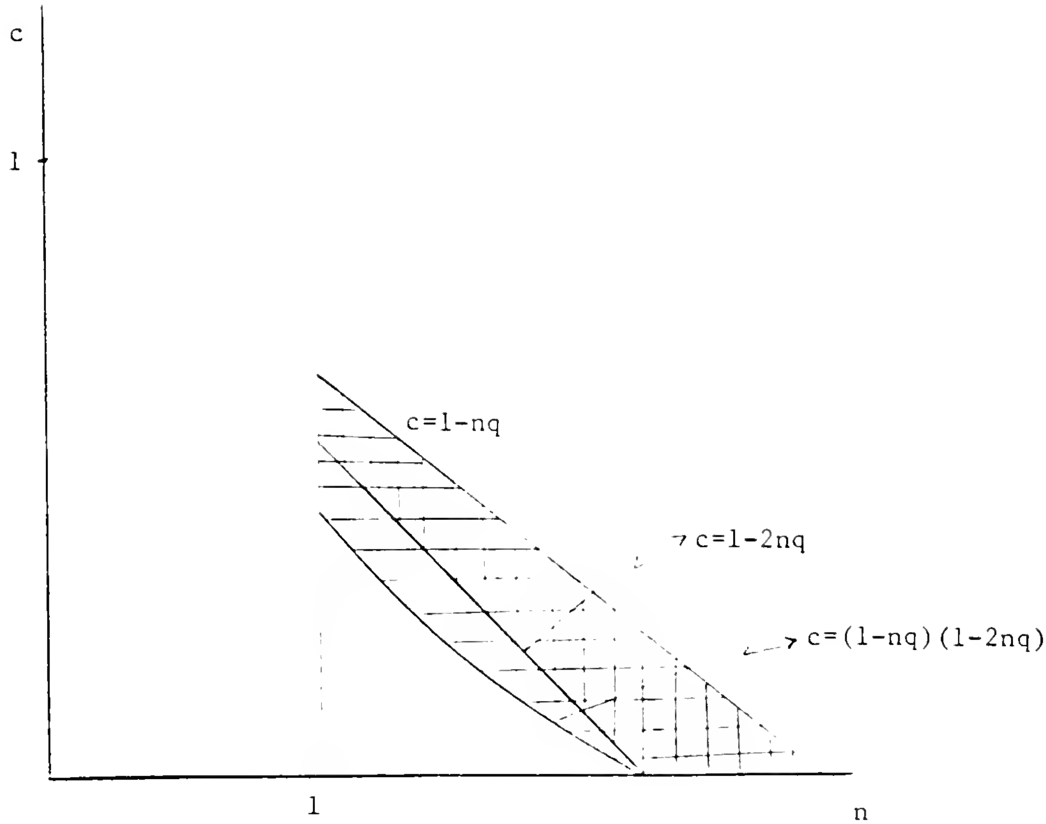

Figure 2: Inefficiency of the Standardization Equilibrium

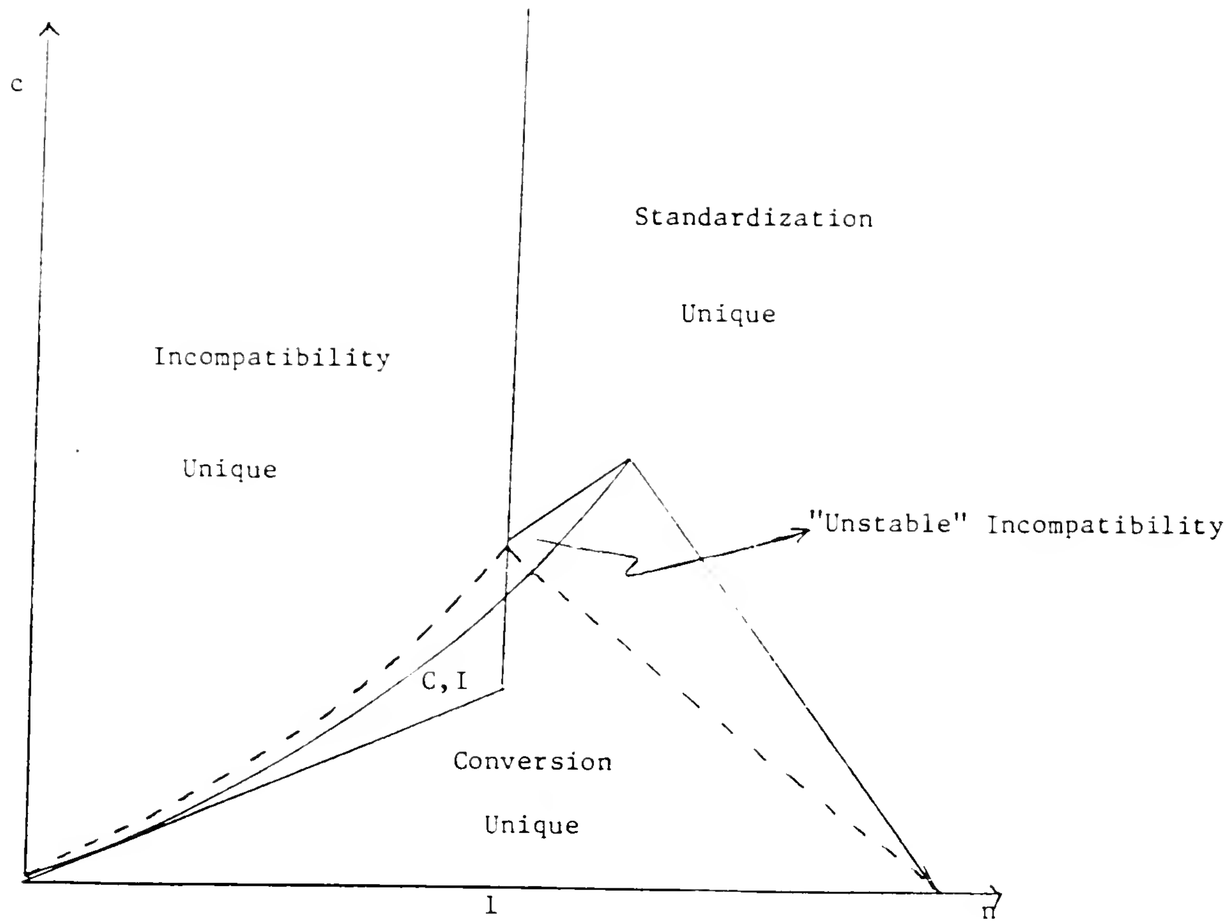

Figure 3: Equilibrium Outcomes Under Duopoly